Application of the CMAQ Model to Better Understand Air Pollution Issues in China

by Jiani Tan, Yangjun Wang, Ling Huang, and Li Li

This article summarizes previous studies using the Community Multiscale Air Quality (CMAQ) model to investigate the sources, formation, and control policies of air pollution, which has contributed to a better understanding of the air quality in China.

Over the past decade, China has suffered from severe air pollution issues related to particulate matter (PM) and ozone (O_3) largely due to its rapid economic development and increase in energy consumption, impeding its goal of sustainable urban development. High levels of PM induce various cardiovascular and respiratory health diseases, leading to millions of annual premature deaths in China.[1] High concentrations of O_3 pollution pose significant health risks to humans, vegetation, and the ecosystem.[2]

The major city clusters affected by poor air quality include the Beijing–Tianjin–Hebei (BTH), the Yangtze River Delta (YRD), the Pearl River Delta (PRD), the Fenwei Plain (FW), and the Sichuan basin (SC) economic circle (see Figure 1a). To combat these issues, the Chinese government implemented the Clean Air Action Plan (CAAP) in 2017 with two goals: reducing emissions from sources such as power plants, industry, and vehicle exhaust, and decreasing PM concentration in major urban districts. A post assessment study found that CAAP achieved significant reductions in sulfur dioxide (SO_2; 62%), oxides of nitrogen (NOx; 17%), and PM (35%).[3] China continued its efforts to reduce air pollution through the Three-Year Action Plan for Winning the Blue Sky Defense Battle (TYP) in 2018, aimed at reducing the numbers of heavily polluted days (daily Air Quality Index higher than 200) by 25% from 2015. Recently, the State Council deliberated and approved the Action Plan for Continuous Improvement of Air Quality, aimed at lowering the concentration of $PM_{2.5}$ at urban regions by 10% and reducing the national emissions of NOx and volatile organic compounds (VOCs) by 10% during 2020-2025.

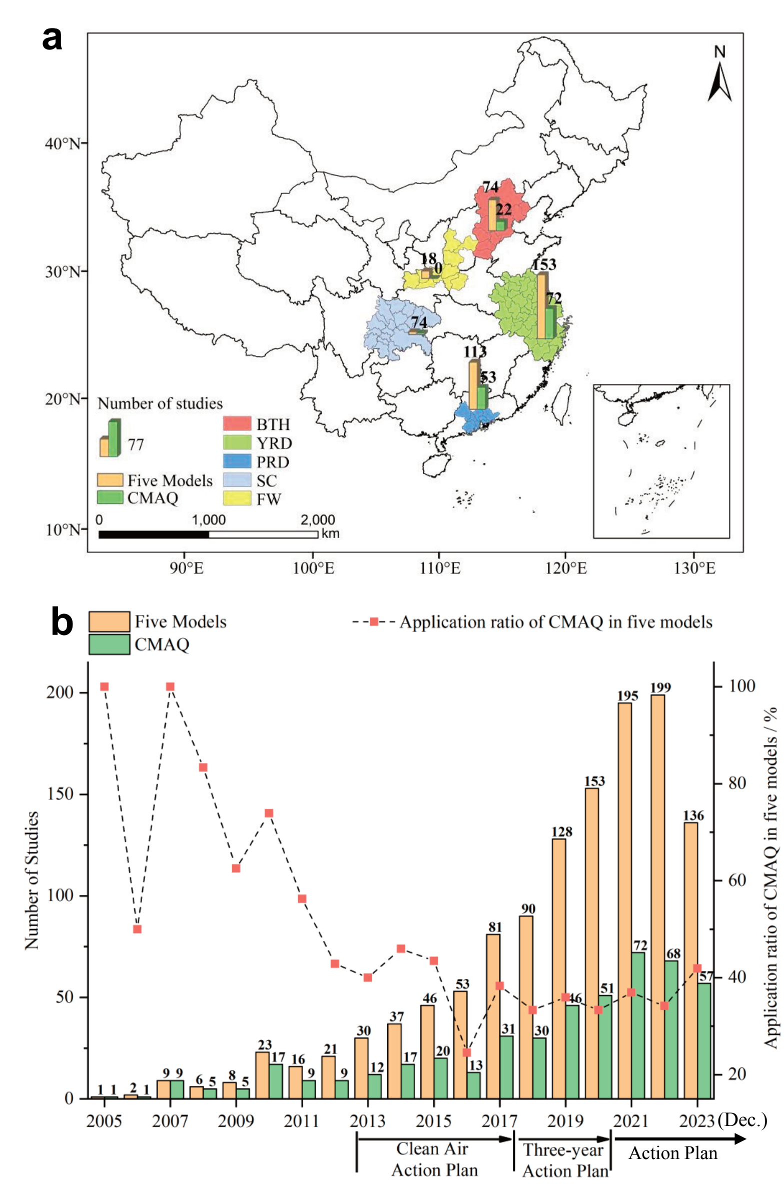

Figure 1. (a) Total numbers of studies published during 2005–2023 that employed AQMs to study air quality issues in the Beijing–Tianjin–Hebei (BTH), the Yangtze River Delta (YRD), the Pearl River Delta (PRD), and the Sichuan basin (SC) economic circle. (b) Numbers of studies that employed AQMs to study air quality issues in China during 2005–2023 (December). The five AQMs include CMAQ, CAMX, WRF-Chem, GEOS-Chem and NAQPMS.

Air quality models (AQMs) have been widely used to investigate the formation and control of air pollution. A series of AQMs has been utilized to aid air quality management in China with a significant increase in the publication after 2013 (see Figure 1b), when haze events in China outbroke[4] and the CAAP was implemented. The most commonly used models include: the Community Multiscale Air Quality model CMAQ; https://www.epa.gov/cmaq); the Comprehensive Air Quality Model with Extensions (CAMx; https://www.camx.com); the Weather Research and Forecasting model coupled with Chemistry model (WRF-Chem; https://ruc.noaa.gov/wrf/wrf-chem); the Goddard Earth Observing System-Chem model (GEOS-Chem; http://geoschem.org); and the Nested Air Quality Prediction Modeling System (NAQPMS) developed by the Institute of Atmospheric Physics of Chinese Academy of Science (IAP-CAS).[5] Among all these models, CMAQ is the most frequently used AQM in the last two decades (see Figure 1b).

Application of the CMAQ Model in China

CMAQ is an open-source modeling system developed by the U.S. Environmental Protection Agency (EPA) and designed for studying air pollution issues at regional-to-global scales. Hundreds of research groups in China have used CMAQ to investigate the sources, formation mechanism, and control strategies of air pollution in China.[6-8] The applications focused on the following areas: (1) Formation mechanism of air pollution; (2) Source apportionment; (3) Air quality forecasting; and (4) Development and evaluation of pollution control strategies (see Figure 2).

Support understanding of the formation and removal mechanism of air pollutants. The chemical mechanism of CMAQ, including the formations of secondary pollutants, and dispersion, long-range transport and deposition of pollutants, is continuously updated according to laboratory, field, and modeling findings. The CMAQ model has been used to study different topics on air pollution in China, such as the non-linear relationship of O_3 to precursor emissions (NOx and VOCs),[9,10] formation of haze pollution,[11,12] the main components of PM (sulfate, nitrate and secondary organic aerosols, or SOA),[13,14] and wet and dry depositions of gas and particle pollutants.[15]

EPA developed several diagnostic modules to support the application in mechanism research. For instance, Li et al.[16] used the Process Analysis tool[17] to evaluate the influences of physical and chemical processes during high O_3 pollution episodes and found a heterogeneous distribution of O_3 pollution that is largely related to emission sources. Wang et al.[10] used the decoupled direct method in three dimensions (DDM-3D) module[18,19] to test the sensitivity of the O_3 pollution to NOx reduction and found that NOx reduction helped to reduce the high peak concentration of O_3 even for the urban areas in VOC-limited regime. EPA developed the two-way coupled model WRF-CMAQ (https://www.epa.gov/cmaq/wrf-cmaq-model) to study the interaction between air pollution and climate, which has shown significant improvements on the spatiotemporal distributions of both PM and O_3 compared to the one-way model.[20]

Conduct source appointment to quantify the contributions of emission sources to air pollution. The CMAQ model can quantify the contribution from individual emission sources by simulating the air pollution concentrations under different emission scenarios.[21] In addition, the CMAQ model can establish source-receptor relationships for air pollution among regions by computing and calculating the air pollution in the transboundary air flows and support the regional-joint prevention and control of air pollution.[22,23] Brute Force Method (BFM) is one of the commonly used methods to conduct source appointment,[24] which is achieved by unning the CMAQ model twice, one with full emissions and another with all emissions except the certain emission source, and the difference between the two cases denotes the contribution. EPA developed the Integrated Source Appointment Method (ISAM), which is a built-in module in CMAQ to facilitate this function without running the model multiple times.[25] Wang et al.,[26] used this module to quantify the contribution of the regional transport of NOx and VOCs to local O_3 formation. In addition, Xing et al.[27] developed the Response Surface Model (RSM) to describe the non-linear relationships between O_3 and precursor emissions for China based on CMAQ simulations under thousands of emission scenarios.

Provide air quality forecasts and severe air pollution warnings. The CMAQ model has shown reasonable performance on predicting the magnitudes of major air pollutants at urban, regional and national scale over China. Air quality forecasting systems for China have been developed by coupling the CMAQ model with meteorological

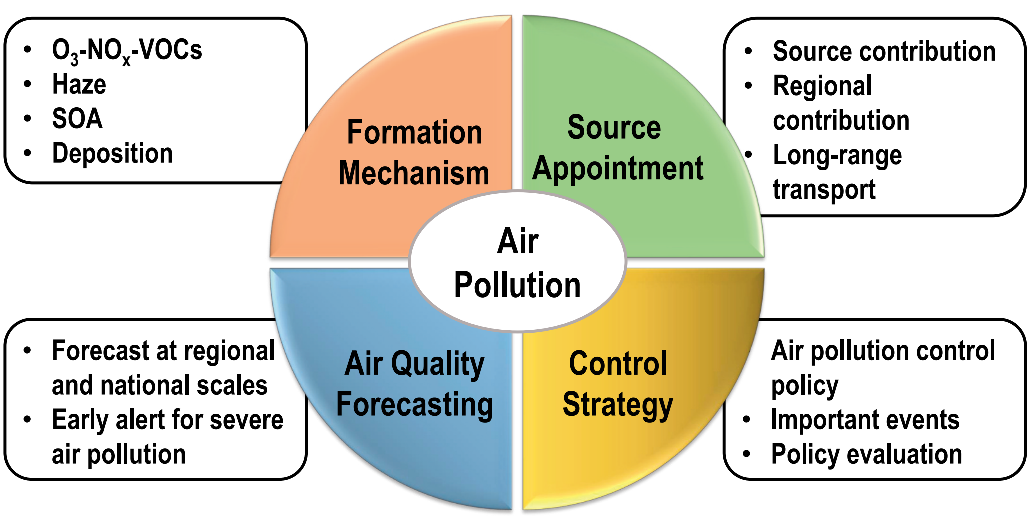

Figure 2. Applications of the CMAQ model in studying air pollution in China.

models.[8,28,29] To improve forecasts of poor air quality and early warnings for severe air pollution, new techniques have been applied to improve the model accuracy. For instance, machine learning techniques have been recently used to correct the model bias on predicting air pollution concentrations[30] and provide short-term air quality predictions.[31]

Develop and assess the effectiveness of pollution control regulatory and policies. The CMAQ model has been widely used in the development and assessment of regional pollution control policies.[32-35] Chen et al.[36] assessed the effectiveness of the TYP on PM pollution in the SC region of China and found a maximum 10% annual reduction in the PM concentration, which avoided 23,000 premature deaths. Elly et al.[37] analyzed the formation and removal of O_3 pollution during the COVID-19 pandemic in the beginning of 2020 when stay-at-home orders reduced emissions from traffic and industry. Using emissions from that period, they found that further reduction of NOx increased O_3 as a disbenefit of emission reduction.

In addition, the CMAQ model is used to provide optimal emission control pathways for air quality during important events such as the Beijing 2008 Olympics Games, the Hangzhou G20 summit and the International Import Expo.[38,39] For example, Li et al.[22] evaluated the effectiveness of regional joint-control strategies on air quality of the YRD region during the 2nd World Internet Conference and pointed out the synergistic emission reduction among the adjacent regions and 48 hours-before-events implementation as the most effective way to guarantee good air quality during the event.

Implications for Future Development

This article covers part of the vast applications of the CMAQ model in China. Besides the abovementioned topics, the CMAQ model is used to predict the air pollution under different future climate scenarios,[40] providing regional air pollution concentrations to evaluate the impact of air pollution on human health[41] and crop yield.[42] Based on the studies in atmospheric science and application in modelling, following are the potential challenges for modelling study in China:

Improving model chemistry mechanism. Laboratory-based, field-measurement-based, and modeling studies bring new findings to atmospheric science. New areas regarding model development and application emerged, such as introducing detailed photochemistry (halogen, HONO, etc.) in the model to understand its contribution to the nitrogen cycle and consequently the formation of PM and O_3 at regional scale; applying explicit presentations for Intermediate-VOC (IVOC) and Semi-VOC (SVOC) species to improve model estimation on the formation of SOA. A companion paper by Pye et al. elsewhere in this issue of *EM* presents information about the development of new chemical mechanism for CMAQ, focusing on the Community Regional Atmospheric Chemistry Multiphase Mechanism (CRACMM) developed by EPA.

Coupling air pollution-climate change. The elevated emission of greenhouse gases (GHGs) contributes to the global warming process. Climate change and air pollution issues are linked by the air pollution-meteorology-climate interactions.[43] Modeling studies in the United States found that mitigation of GHGs could co-benefit the air pollution and climate change problem.[44] China is taking active actions to achieve the goal of net-zero emission and carbon neutrality, together with the goal to control air pollutants. The Chinese Government and scientific community are looking for solutions for a synergic control of both GHGs and air pollutants and call for studies on the emission, transport and removal of GHGs and the mitigation strategies. **em**

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